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Crossed-Beam Measurements of the Diffuse Radar Aurora

W. L. Ecklund, B. B. Balsley and R. A. Greenwald
Aeronomy Laboratory
National Oceanic and Atmospheric Administration
Boulder, Colorado 80302

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ABSTRACT

Two widely separated 50 MHz Doppler radars were used during April, 1973, to simultaneously examine the diffuse radar aurora in a spatially limited common area. The permanent NOAA radar at Anchorage and a portable NOAA radar located at Aniak, Alaska, were operated with antennas having narrow beams that crossed north of College, Alaska, defining an area 40 km on a side. The two radars provided a unique measurement of aspect sensitivity, and a value of approximately 8 dB/degree was obtained with this system. The scattering cross-section of the diffuse radar aurora was determined to be essentially the same at the two observing azimuths which were separated by 43°. In addition, Doppler spectra obtained at the two sites indicate the diffuse radar auroral irregularities are similar in some respects to equatorial type II irregularities. However, in this experiment we find two distinct velocity components for the drifting irregularities. Both components maximize in the same direction, but have significantly different magnitudes which suggests that the irregularities associated with these two Doppler components may be occurring at different altitudes. We have inferred a northward E-region electric field of 20 to 30 mv/m from the crossed-beam auroral radar data while simultaneous measurements with the nearby Chatanika incoherent scatter radar indicated an inferred northward F-region field component of about 50 mv/m.

INTRODUCTION

In the past most high spatial resolution studies of the radar aurora have been done with radar systems using steerable antennas and operating at frequencies higher than several hundred MHz. With these systems, if one assumes spatial uniformity of the irregularity structure, it has been possible to determine the aspect angle dependence of radar auroral backscatter and the azimuthal dependence of the spectral characteristics of the returned signals [Leadabrand et al., 1965; Chesnut et al., 1968; Abel and Newell, 1969; and Hagfors et al., 1971]. In order to have a good spatial resolution at lower frequencies, radar systems require large fixed azimuth antennas. Obviously, a large number of fixed-azimuth antennas are required to simulate the continuous azimuthal coverage provided by steerable antennas. However, for elementary azimuthal studies of the radar aurora, a few such antennas are sufficient. For example, at 50 MHz Ecklund et al. [1973] used two narrow-beam antennas separated in azimuth by about 45° to compare the Doppler spectra of the diffuse radar aurora. In this study, as in all of the previous studies at higher frequencies using steerable antennas, it was necessary to assume uniformity of the irregularity structure over distances of several hundred km for periods of time sufficient to observe the azimuths of interest.

Clearly, it would be more desirable to examine a single scattering volume simultaneously from two or more directions so that assumptions about spatial and temporal uniformity of the irregularity structure would be unnecessary. With this objective in mind, a portable 50 MHz radar system was temporarily installed at the White Alice Communication site at Aniak, Alaska, during April 1973. This system was used in conjunction with the permanent 50 MHz system at Elmendorf Air Force Base near Anchorage, Alaska, which has been used for a variety of recent radar-auroral studies [Ecklund and Unwin, 1971; Balsley and Ecklund, 1972;

Balsley et al., 1973; Ecklund et al., 1973; and Greenwald et al., 1973]. The present experiment was designed to examine the scattering volume delineated by the intersection of the Aniak and Anchorage antenna beams in order to determine the dependence of the scattering cross-section on both aspect angle and azimuth. The system was operated only for a few days, and a limited amount of data were obtained on the diffuse type of radar aurora. An additional, unexpected result was the observation of two distinct velocity components in the drifting irregularities associated with the diffuse radar aurora.

EXPERIMENTAL PARAMETERS

Operating parameters for the two radars are given in Table 1. Note that the characteristics of the two systems are quite similar, except for their peak transmitted powers and antenna azimuthal beamwidths. A relatively complete description of the systems, as well as an outline of the analysis technique, appears in Balsley and Ecklund [1972].

The locations of the two radars and their associated antenna patterns are shown in Figure 1. The 4° (azimuthal) antenna beam of the Aniak system intersects the 1° Anchorage beam in the region between College and Fort Yukon. The Anchorage antenna is directed roughly perpendicular to the L contours (also shown in the figure) while the Aniak antenna looks more along these contours.

A more detailed picture of the beam-intersection region appears in Figure 2, including aspect angle contours for both systems. The aspect angle (ϕ) is the angle between the antenna beam and the magnetic field (neglecting refraction), and in this case is determined at a height of 110 km above the earth's surface. Within the intersection region $\phi_{\text{Aniak}} \approx 91^{\circ}$, while $92^{\circ} < \phi_{\text{Anchorage}} < 93^{\circ}$.

DATA PRESENTATION

Although the geomagnetic activity was relatively low, and the radar-auroral echoes were correspondingly weak during the short observational period, reasonably

good data were obtained on the evening of U.T. day 5 April 1973. During this period the radar aurora was the diffuse type associated with the evening electrojet [Greenwald et al., 1973]. The presence of the electrojet near the crossed-beam common volume is also indicated by the positive bay in the H component on the College magnetogram, Figure 3, with two peaks at 0640 and 0745 U.T.

Aspect Sensitivity and Cross-Section

Simultaneous profiles of relative back-scattered power at Anchorage and Aniak at 0641 U.T. are shown in Figure 4a. Since the diffuse echo is typically very extended east-west along L contours, the power profiles have been plotted against L so that they can be compared at locations other than where the beams cross at L = 5.9 (see Figure 1). Note that equatorward of L = 5.7 the Anchorage power decreases smoothly, whereas the Aniak power is relatively constant. This is due to the fact that in this region $\phi_{\text{Anchorage}}$ departs from 90° more rapidly than ϕ_{Aniak} (see also Figure 2). In order to investigate this dependence quantitatively, we assumed that the backscattered power (P) at each station could be represented as:

$$P = \frac{Ae^{-C|\phi-90^{\circ}|}}{r^{3}} \tag{1}$$

where A includes backscatter cross-section and system constants such as transmitted power, antenna configuration, etc. C is related to the aspect sensitivity, ϕ is the aspect angle, and r is the range to the backscattering region. We assume an r^{-3} range dependence on the scattered power since for the diffuse radar aurora the antenna beam is filled in azimuth but not in elevation. Then:

$$\ln\left[\frac{(Pr^{3})_{\text{Anch}}}{(Pr^{3})_{\text{Aniak}}}\right] = \ln\frac{A_{\text{Anch}}}{A_{\text{Aniak}}} - C(\phi_{\text{Anch}} - \phi_{\text{Aniak}}) \tag{2}$$

Note that $\phi_{\text{Anchorage}}$ is greater than ϕ_{Aniak} at 110 km altitude for this experiment. The data points shown in Figure 4b were obtained by measuring the profiles in 4a from L = 5.3 to 5.9 and plotting the power ratios as expressed in Eq. (2). The slope of the straight line fitted to the data points gives a value for C of 1.86 which indicates an aspect sensitivity of 8.1 dB/degree. The fact that the data points can be fitted by a straight line seems to justify our empirical adoption of an exponential form for the aspect angle dependence in Eq. (1).

At the point where $\phi_{\text{Anch}} - \phi_{\text{Aniak}} = 0$, the line in Figure 4b intersects the $(Pr^3)_{\text{Anch}}/(Pr^3)_{\text{Aniak}}$ axis at a value of 12. This indicates that when the effects of aspect sensitivity and range dependence are removed, the backscattered power received at Anchorage exceeds the Aniak power by about 11 dB. A careful comparison of the Anchorage and Aniak system constants listed in Table I (transmitted powers, antenna configurations, receiver bandwidths and feed-line losses) shows that the Anchorage radar system should have about a 10.5 dB advantage over the Aniak system. Thus, we may also conclude that the data for 0641 U.T. (Fig. 4) indicate that the cross-section of the diffuse radar aurora is approximately the same at azimuths separated by 43°.

Additional measurements of the aspect sensitivity and cross-section of the diffuse radar aurora for eight different times during this evening are given in Table II. The values for aspect sensitivity are remarkably constant even though these measurements cover a period of almost one and one-half hours. During this time 10 sets of simultaneous measurements were made, and only two sets (0740 and 0741 U.T.) did not approximate a straight line when plotted in the manner shown in Fig. 4b. This result is interpreted as being due to longitudinal structure in the scattering region during these two periods. The second column in Table II shows the amount by which the observed Anchorage to Aniak power difference (11 dB at 0641 U.T. in the example shown in Fig. 4)

varies from the expected 10.5 dB difference due to known system parameters. All of these determinations fall close to zero, providing additional support for the result of 0641 U.T. which showed the scatter cross-section is about equal at the azimuths of Anchorage and Aniak.

The values for aspect angle (ϕ) used in the preceeding analysis were obtained by neglecting refraction. Unwin [1966] has shown, however, that refraction effects can be important, particularly at lower VHF frequencies. To determine the effect of refraction during this experiment, electron density profiles obtained from the crossed-beam region by the Chatanika incoherent scatter radar [Leadabrand et al., 1972] were provided by M. Baron (private communication). These electron density profiles were obtained for two periods (0645 to 0650 and 0747 to 0752 U.T.) during the experiment. The profile for the 0747 to 0752 U.T. period had slightly higher electron densities than the 0645 to 0650 U.T. period, and was used in a ray tracing program (Jones and Stephenson, 1974) to determine the amount by which the Aniak and Anchorage radar beams were refracted in propagating to 111 km altitude. This is the altitude that Unwin [1959] found for the maximum occurrence of diffuse radar aurora at 55 MHz. The results of the ray tracing program show that at $L = 5.9$ refraction decreases the aspect angle for the Aniak radar by 0.65° and for the Anchorage radar by 0.49°. This 0.16° difference increases to 0.18° at $L = 5.3$ where the Aniak and Anchorage aspect angles are decreased by 0.56° and 0.38°, respectively. The result of including the refraction effects is to move the points in Fig. 4b to values of $\left[\phi_{\text{Anchorage}} - \phi_{\text{Aniak}}\right]$ larger by 0.16° to 0.18°. This has the effect of decreasing the slope slightly and increasing the intercept point by a small amount. Thus, refraction decreases the values for aspect sensitivity listed in column one of Table II by 0.1 to 0.2 dB/degree and increases the values in column two by one dB.

Two Station Spectra

A set of simultaneous Doppler spectra (relative echo power vs. frequency shift from the transmitted frequency) obtained at Aniak and Anchorage from within 30 km of the common scattering volume is shown in Figure 5. These spectra were obtained during the period of the first electrojet current maximum shown in Figure 3. They are typical of the spectra obtained during the complete experimental period. Note that, while the Anchorage spectrum has a slightly negative Doppler shift, the Aniak spectrum is shifted toward positive values and exhibits the presence of two distinct components.

This apparent difference in the Anchorage and Aniak spectral shifts can be understood, at least on a qualitative basis, by referring to the L-contour geometry shown in Figure 1. The Anchorage antenna is directed nearly perpendicular to the L contours (actually the beam is directed slightly toward the west), while the Aniak beam looks eastward and more along the contours. Since the electrojet current and the associated diffuse irregularity velocity tend to maximize along L contours [Leadabrand *et al.*, 1965], one would expect that the Anchorage spectra would display a lower shift than the Aniak spectra for a given irregularity drift velocity. If the maximum velocity is exactly along L contours, then the Anchorage spectra--because of the slight westward direction of the antenna beam--would be shifted in a direction opposite to that of the Aniak spectra. This feature is clearly apparent on the spectra seen in Figure 5a.

If we further assume that the two-component Aniak spectrum indicates a double peak in the velocity distribution of the irregularities, then the single-peaked Anchorage spectrum may indicate that both components have been shifted toward zero and are nearly superimposed. This feature is demonstrated in the spectrum shown in Figure 5c. In this figure the dashed curves represent two Gaussian components

whose relative amplitude, width, and displacement have been adjusted to fit the Aniak spectrum (5b) when added together. The solid curve in Fig. 5c shows the superposition of these two dashed curves (amplitude normalized) after each has been shifted by the cosine-dependent factor expected for Anchorage if the irregularities are moving along L contours. Comparison of the synthesized Anchorage spectrum (solid curve in 5c) and the actual Anchorage spectrum (5a) shows that the above assumptions of a two-component irregularity velocity distribution along L contours are quite reasonable. Greenwald *et al*. [1974] show that the diffuse radar aurora often displays these two spectral components which they refer to as "broad" and "narrow" on the basis of their spectral widths. The narrow component typically exhibits a smaller Doppler shift relative to the broad component, as shown on the Aniak spectrum.

Drift Analysis

If we assume that the mean radial drift measured by each radar varies as the cosine of the angle between the radar beam and the direction along which the irregularity velocity maximizes (V_ψ), then we can use the two radars to unambiguously determine the magnitude and direction of V_ψ for both the broad and narrow spectral components. The validity of the assumption concerning the cosine dependence will be discussed later. Several determinations of the magnitude and direction of V_ψ were made during the experimental period and the results have been tabulated in Table III. Note that the directions of V_ψ determined at the four different times indicated in the table are essentially the same for both the narrow and broad components, and that they are directed westward approximately along L contours (geomagnetic west corresponds to about 295° geographic). These directions agree to within 10° of the horizontal current directions deduced from the College magnetometer D and H components. Note also that, although the directions of V_ψ for the broad and narrow com-

ponents are the same, there is a consistent difference between their magnitudes. The values for the narrow component range between 350 and 420 m/s, while the broad component falls between 550 and 650 m/s.

DISCUSSION

Our measurement of aspect sensitivity of the diffuse radar aurora gives a value of about 8 dB/degreee which is considerably higher than our previous estimate of 3 to 4 dB/degree [Greenwald et al., 1973]. Other determinations of radar auroral aspect sensitivity have ranged from 10 dB/degree [Leadabrand et al., 1967] to less than 2 dB/degree [McDiarmid, 1972]. We believe the values presented here are the most accurate currently available at 50 MHz, for aspect angles within 2 to 6° of perpendicularity, since the use of two radars required only minimal assumptions about the spatial uniformity of the scatter intensity.

Using the ≈ 8 dB/degree aspect angle dependence, our results show that the diffuse radar aurora scatters about equally well on the azimuths of the Anchorage and Aniak radars. These radar beams are separated by 43° in azimuth; the angle between the Anchorage beam and geomagnetic north is 13° W while the corresponding angle for Aniak is 30°E. While this is a crude measurement of the azimuthal dependence of the scattering cross-section of diffuse radar aurora, it is, to our knowledge, the first such measurement in which only minimal assumptions about spatial uniformity of the irregularity region were required.

Furthermore, the diffuse radar auroral spectra obtained from this crossed-beam experiment indicate two significant results. First, both the broad and narrow spectral components of diffuse radar aurora, that are commonly observed with the Anchorage radar [Greenwald et al., 1974], are also observed from Aniak. Second, simultaneous measurements with two radars of nearly coincident scattering

volumes indicate that the width and relative amplitude of each spectral component are the same at the two azimuths, while the mean Doppler shift is azimuth dependent.

These spectral results, and the isotropy of the scattering cross-section with azimuth suggest that the diffuse radar auroral irregularities are similar to the type II irregularities in the equatorial electrojet [Farley and Balsley, 1973]. The equatorial type II irregularities arise via turbulent cascading from large-scale structures that are generated by the gradient-drift instability. The type II irregularities are convected along with these larger structures. This concept of turbulent cascading in the equatorial electrojet has been treated quantitatively by Sudan _et al_. [1973], and Greenwald [1974] has applied their formalism to the diffuse radar aurora.

The values for V_ψ in Table III would represent the direction and magnitude of the large scale irregularities in the turbulent cascading model. In order to deduce these values for V_ψ, we assumed that the mean radial irregularity drift measured by each radar varied as the cosine of the angle between the radar beam and V_ψ. While this assumption of an azimuthal cosine dependence is consistent with the turbulent cascading model, it is not supported by some past higher frequency radar studies. In fact, Abel and Newell [1969], using a frequency of 1295 MHz, noted that the mean irregularity phase velocity changed from large positive to large negative values as the radar beam was scanned over a few degrees of azimuth about magnetic north. At larger angles with respect to magnetic north there was little change in the apparent radial phase velocity. Similar results were obtained by Chesnut _et al_. [1968] at frequencies of 850 and 1210 MHz and by Tsunoda (private communication) at 398 MHz. However, Leadabrand _et al_. [1965] observed that at a radar frequency of 401 MHz the mean Doppler shift of the radar backscatter varied smoothly with azimuth in a manner

that could be approximated by a cosine dependence. Chesnut et al. [1968] observed similar behavior at 139 and 398 MHz and suggested that irregularities observed above approximately 500 MHz had different spectral characteristics than those observed at lower frequencies. Spectral observations of irregularities in the equatorial electrojet support his idea. Balsley and Farley [1971] performed a 3-frequency study of equatorial backscatter and observed predominately type II (gradient drift) spectra at 16 MHz, both type I (two-stream) and type II spectra at 50 MHz and only type I spectra at 146 MHz. For the auroral case discussed above, the higher frequency results would be similar to those obtained for type I spectra seen at the equator which exhibit Doppler shifts that change from large positive to large negative values over a range of observing angles of a few degrees about perpendicular to the electrojet current. The lower frequency auroral results would correspond to the type II equatorial spectra which exhibit cosine dependent mean Doppler shifts [Balsley, 1969].

One of the more interesting results from the crossed-beam measurements is that while the values of V_ψ for the broad and narrow spectral components are in the same direction, they have significantly different magnitudes. There may be several possible explanations for the presence of these two spectral components with differing magnitudes of V_ψ. Perhaps the most plausable interpretation is that the irregularities associated with the broad and narrow components occur at two different altitudes. Some evidence for two distinct irregularity layers in the diffuse radar aurora has been presented by Abel and Newell [1969]. If the irregularities are occurring at different altitudes, then the irregularity propagation characteristics and/or the electric field strength may be appreciably different, which would explain the two distinct values that we find for the magnitude of V_ψ.

Finally, _if_ we assume that V_ψ is equal to the electron drift velocity then we can deduce the magnitude and direction of the electric fields in the irregularity layers associated with the broad and narrow components. These inferred northward electric fields range from 20 mV/m for the narrow component irregularities to 30 mV/m for the broad spectral component. During this period the incoherent scatter radar at Chatanika, Alaska, [Leadabrand _et al._, 1972] was observing plasma drifts in a region near our crossed-beam volume. Preliminary analysis of this data from 175 km altitude was used to infer an average northward electric field component of approximately 50 mV/m (M. Baron, private communication). A more complete comparison of electric fields deduced from the Chatanika incoherent scatter radar and the Anchorage auroral radar is planned in order to assess the significance of the preliminary results presented here. In addition, we hope to investigate the altitude dependence of the diffuse radar auroral irregularities in the near future by modifying the present Anchorage radar to obtain 5 km or better altitude resolution.

TABLE I

RADAR SYSTEM PARAMETERS

PARAMETER	ANCHORAGE RADAR	ANIAK RADAR	ANCHORAGE ADVAMTAGE (dB)
Frequency, MHz	49.92	49.92	
Peak Pulse Power, kW	30	7	~ + 6
Pulse Width, μS	44	33	~ + 1
Pulse Repetition Frequency, Hz	100-800	100-800	
Receiver Noise Figure, dB	<4	<4	
Receiver Bandwidth, kHz	10	7	~ - 1.5
Antenna Bearing, Geomagnetic	13°W	30°E	
Antenna Feedline Loss, dB	1.5	.5	~ - 1.0
Antenna Beamwidth:			
Azimuth	<1°	<4°	~ + 6
Elevation	≃15°	≃15°	+ 10.5 dB total

TABLE II

5 April 1973

Time (U.T.)	Aspect Sensitivity (dB/deg.)	$\left(\frac{A_{Anch}}{A_{Aniak}} - \text{Expected Systems Difference}\right)$ (dB)
0626:30	7.9	-4
0631	8.0	-3
0640:05	7.8	-2
0641	8.1	0
0645	8.0	+1
0646	6.8	-2
0747	6.9	-3
0748	8.2	0

TABLE III

5 April 1973

Time (U.T.)	Spectral Component	Maximum Drift Velocity	Geographic Azimuth of Maximum Drift
0637	Narrow	375 m/s	293°
0637	Broad	560 m/s	290°
0642	Narrow	420 m/s	291°
0642	Broad	655 m/s	291°
0647	Narrow	385 m/s	290°
0647	Broad	650 m/s	292°
0744	Narrow	350 m/s	288°
0744	Broad	550 m/s	289°

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FIGURE CAPTIONS

Figure 1. Map of Alaska showing the Anchorage and Aniak crossed radar beam. The contours are for L = 5 and 6.

Figure 2. Map of the crossed-beam area showing the Aniak (double-hatched) and Anchorage (single-hatched) radar beams. Range in km from each site is indicated along the beam. The aspect angle contours for Aniak are dashed while the Anchorage contours are solid. Both sets of aspect angle contours are measured as shown in the inset.

Figure 3. College magnetogram. The arrows show direction of increase, and the arrow lengths show the sensitivity for each component. The diffuse radar aurora is associated with the positive bay in H with peaks at 0640 and 0745 U.T. The shaded bands indicate periods when crossed-beam observations were made.

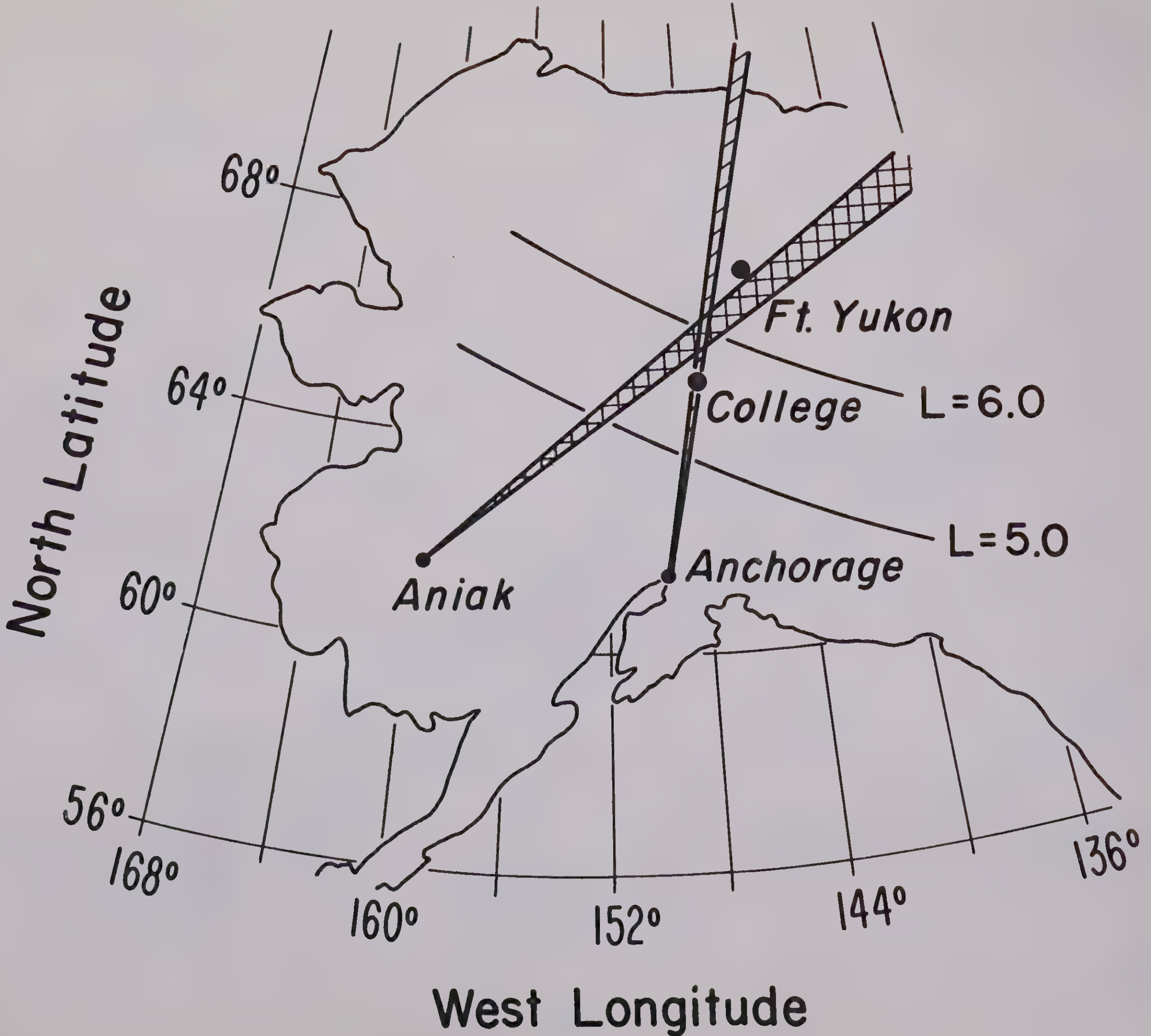
Figure 4. (a) Simultaneous profiles of backscattered power as a function of L for Anchorage and Aniak. The scales at the top give the 110 km altitude aspect angles in degrees (not corrected for refraction) for the two stations.

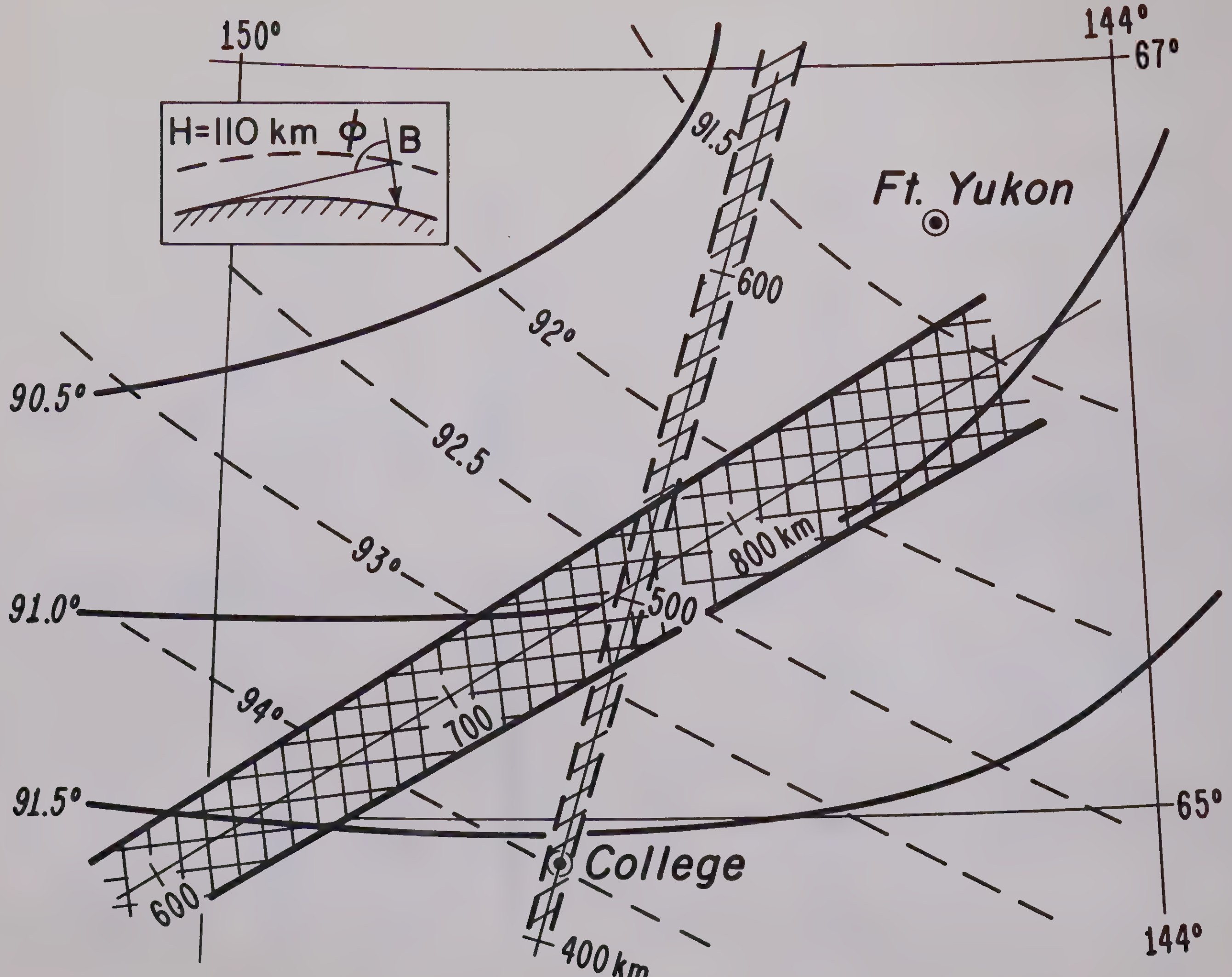
(b) Semi-log plot of the ratio of the Anchorage to Aniak backscattered powers as a function of their aspect angle difference in degrees. The error bars are an estimate of the maximum uncertainty for each point and are derived from the profiles in (a) and the corresponding noise levels which are not shown.

Figure 5. (a) Doppler spectrum from the crossed-beam region observed at Anchorage.

(b) Doppler spectrum from the crossed-beam region observed at Aniak.

(c) The dashed curves represent two Gaussian components that fit the Aniak spectrum when added together. The solid curve shows the superposition of the dashed curves after they were normalized and shifted by the cosine-dependent factor expected for Anchorage.


North Latitude
68°
64°
60°
56°
168°
160°
152°
144°
136°
West Longitude
Ft. Yukon
College
L=6.0
L=5.0
Anchorage
Aniak


150°
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67°
H=110 km
Φ
B
91.5
Ft. Yukon
600
92°
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93°
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College
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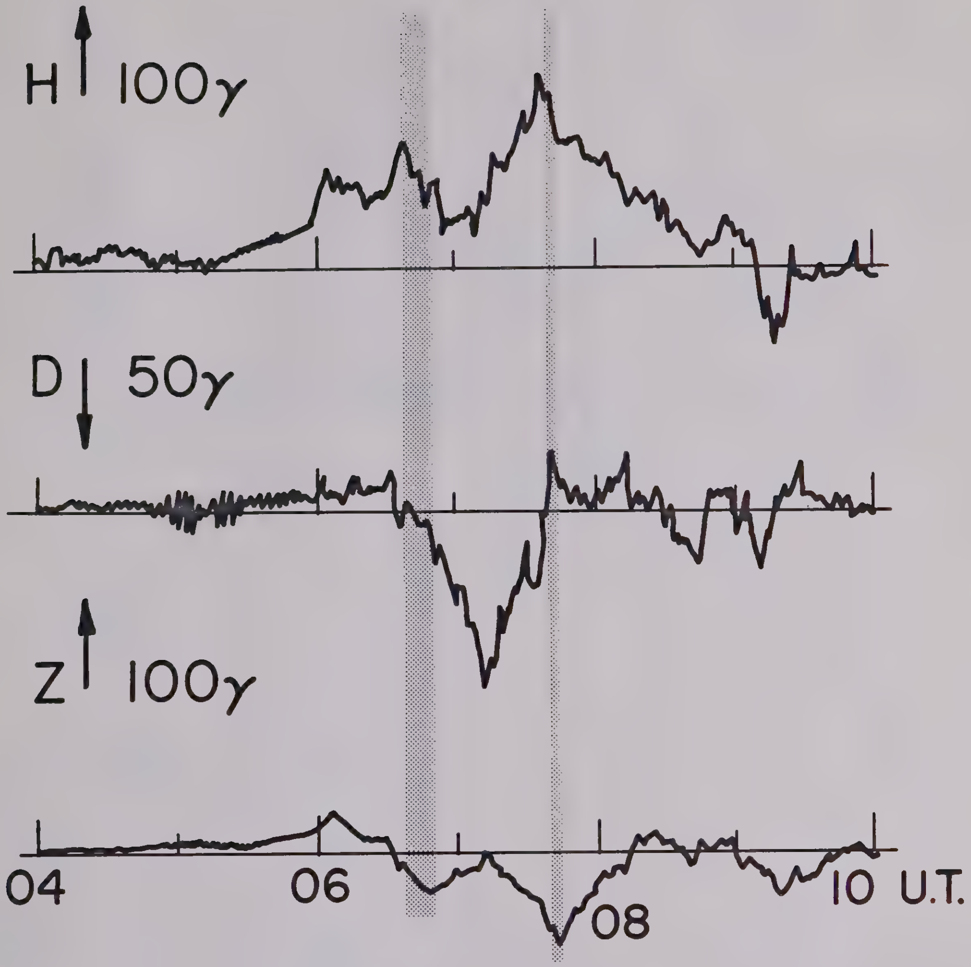
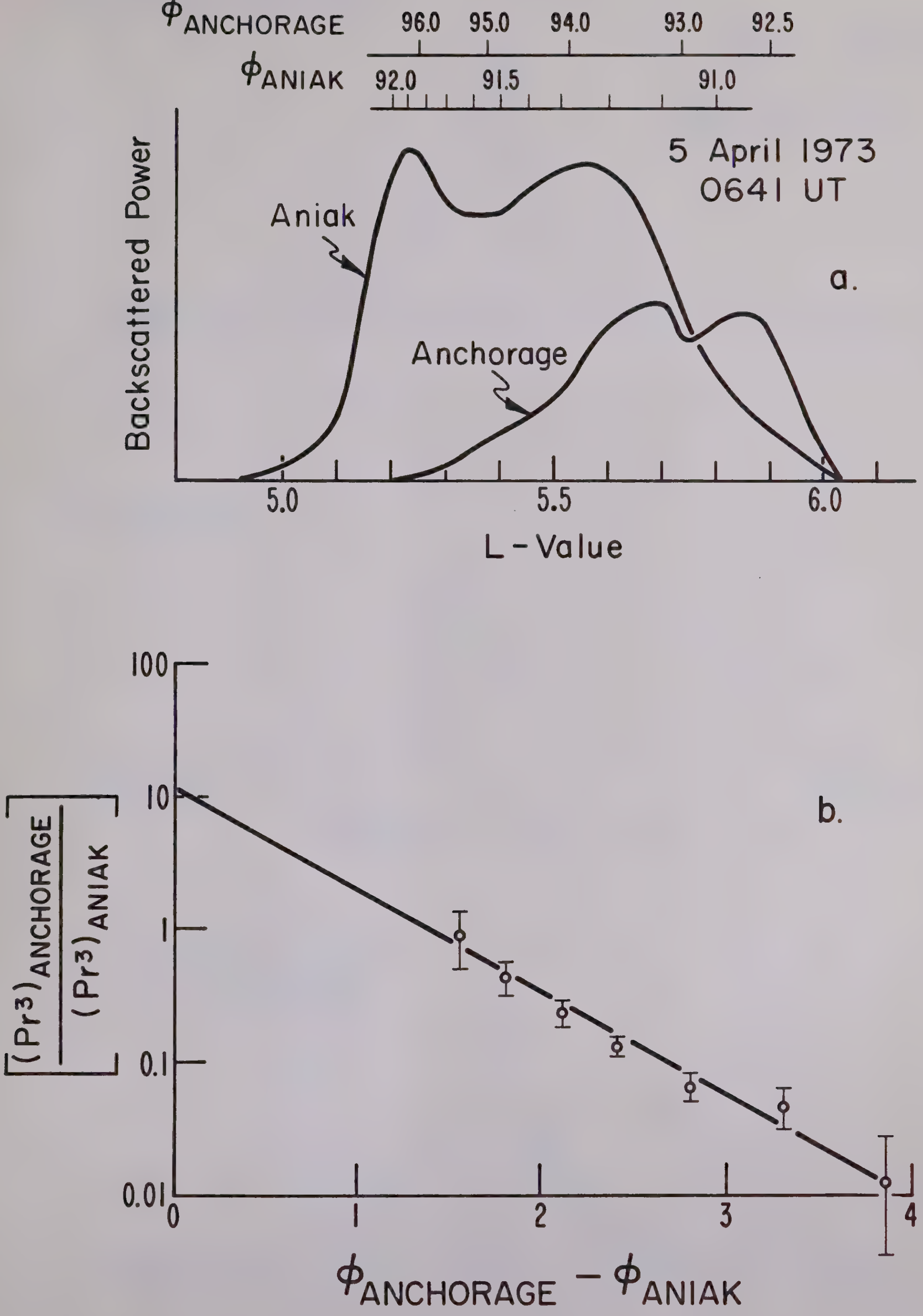


College, Alaska
5 April 1973


$\phi_{ANCHORAGE}$
96.0
95.0
94.0
93.0
92.5
ϕ_{ANIAK}
92.0
91.5
91.0
5 April 1973
0641 UT
a.
Aniak
Anchorage
Backscattered Power
5.0
5.5
6.0
L - Value
100
10
1
0.1
0.01
b.
$\left[\frac{(Pr^3)_{ANCHORAGE}}{(Pr^3)_{ANIAK}}\right]$
0
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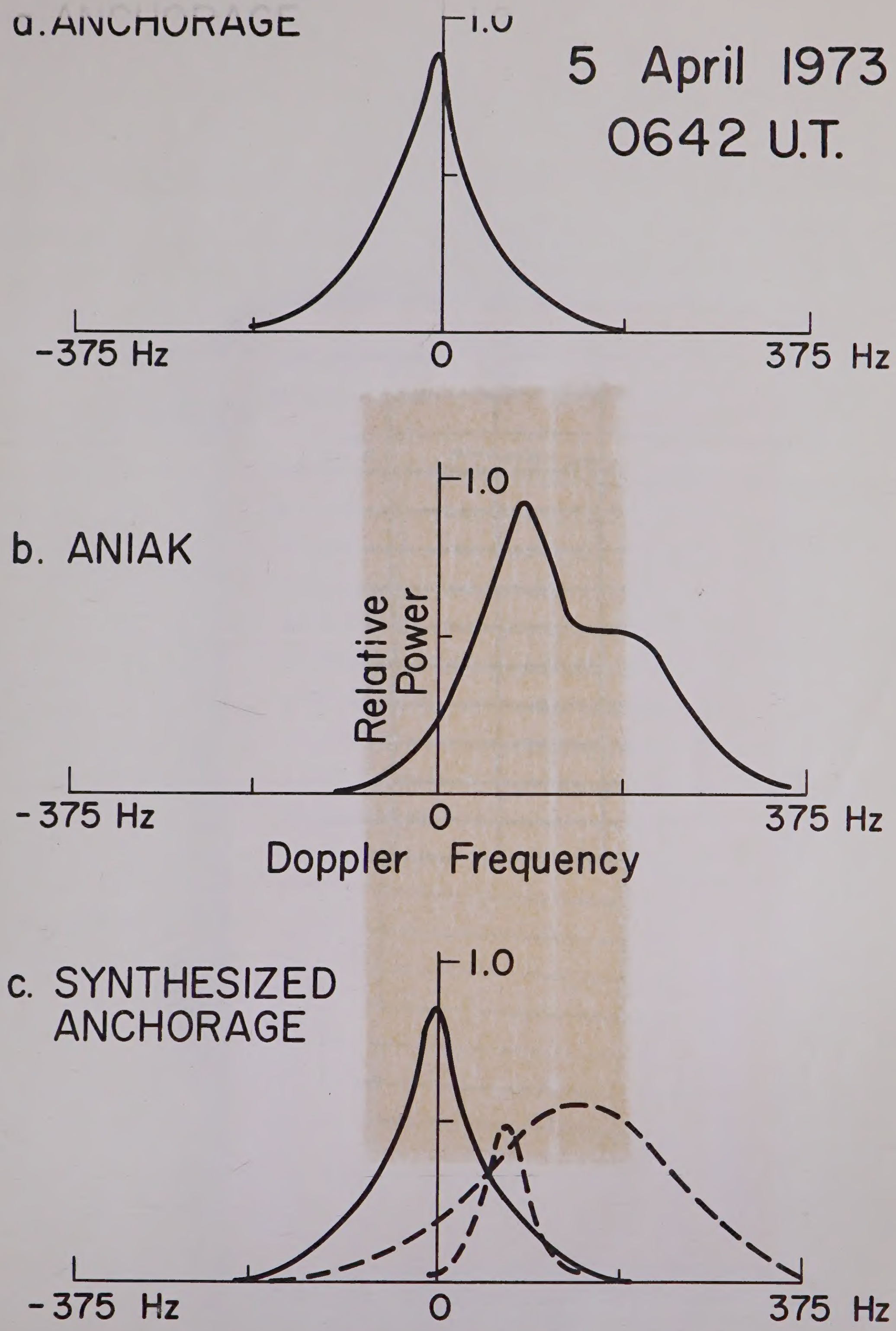
2
3
4
$\phi_{ANCHORAGE} - \phi_{ANIAK}$

75x 3055


a. ANCHORAGE
1.0
5 April 1973
0642 U.T.
-375 Hz
0
375 Hz
b. ANIAK
1.0
Relative Power
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Doppler Frequency
c. SYNTHESIZED ANCHORAGE
1.0
-375 Hz
0
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